Plan of Lecture
The Interstellar Medium

We'd like to know how stars form.

First step: the raw materials.

Gas, dust between stars.

The interstellar medium.

Phases and causes.

What is the ISM?

We'll start with just the facts, then figure out how we know them.

Between stars one finds very tenuous gas and dust.

- **Density: 0.001 to 10^8 per cm^3.**
- **Temperature: 10 K to 10^6 K.**
- **Some diffuse, some in nebulae.**

Star formation is associated with some types of nebulae.

Detecting the ISM

What are ways that we can actually see parts of the ISM?

An *emission nebula* produces bright lines.

A *reflection nebula* acts as a mirror.

An *absorption nebula* blocks out background.

Absorbs blue more than red.

Blue sky, red sunset!

But why is a nebula of a particular type?

Absorption, Emission, Reflection

Going deeper, *why* would a nebula absorb, emit, or reflect?

A nebula does a little of each.

Photons towards you: after absorption, re-emitted in new direction.

Less flux in your direction.

More flux somewhere else!

Emission predominates if nebula is heated.

E.g., star formation inside!

Molecular Clouds

But, physically, what are nebulae?

Fairly dense (10^{2-8} atoms per cm^3).

Relatively cool (10-100 K).

At such temperatues and densities, molecules form.

Thus, molecular clouds.

These can be up to $10^{6-7}\,M_\odot$ (giant molecular clouds), or down to clumps of $\sim 1\,M_\odot$. Bigger ones are less dense.

These are the sites of star formation!

Observing Molecular Clouds

How do we learn about molecular clouds?

Problem: a cloud can block out all light behind it.

How massive is the cloud?

No upper limit!

There needs to be some way to "see through" more of the cloud.

Longer wavelengths go through more stuff.

E.g., center of galaxy.

Invisible in optical.

Visible in infrared.

Could also look for lines.

New possibilities for molecules.

Molecular Transitions

For a single atom, spectral lines can only be produced by electronic transitions.

Fairly high energy.

UV, optical IR.

Molecular clouds are too cool to produce these transitions.

But molecules can do other things.

Vibration.

Rotation (lowest energy).

These take less energy than electronic transitions.

Radio, microwave!

Specific transitions help probe molecular clouds.

Molecular Lines

What lines should we look for? Start with most common atoms.

H and He.

But helium doesn't form molecules; only high-energy electronic transitions.

H forms H_2, but this is a very light molecule.

Quantum: minimum rotation!

Light molecules have high energy.

H_2 needs $T > 500$ K to excite!

Need more massive molecules. Next most common: CO.

Only needs ~5 K to excite.

Good probe of clouds.

Most mass (H_2) undetectable.

Yet More On Lines

Molecular clouds are wonderful for observations of lines.

Cold and tenuous.

Few collisions, so sharp lines.

More than 100 different molecules have been seen.

Glycine, and amino acid!

Also alcohol...

Sharpness of lines allows measurement of velocities (by Doppler shifts), temperatures (by line ratios), and other properties.

Other Parts of the ISM

Not everything is in molecular clouds.

Also have a hot component ($\sim 10^6$ K) and a warm component ($\sim 10^{3-4}$ K).

Hot component is low-density, < 0.01 atoms per cm^3.

Atomic, ionized.

Warm component often has ~ 1 atoms per cm^3.

Atomic but neutral.

The hot component makes up most of the volume of interstellar space.

Some discussion of one or two other phases.

But why only a few? Why not all possible combinations of temperature and density?

Pressure Balance

Consider our three phases.

Molecular: $T = 100$ **K,** $n = 100$ **cm**$^{-3}$**.**

Warm: $T = 10^4$ **K,** $n = 1$ **cm**$^{-3}$**.**

Hot: $T = 10^6$ **K,** $n = 0.01$ **cm**$^{-3}$**.**

Note: nT is about the same in all three.

Pressure balance, $P = nkT$**.**

If phases did not have similar pressure, what would happen?

High-pressure expands.

Low-pressure contracts.

Expansion cools, so T drops and n drops, thus P drops. Pressure balance is reached.

But why not all possible temperatures?

Phases and Cooling

Suppose you have a part of the ISM at some temperature.

Will it stay that way long?

If not, won't see that phase.

How do things cool?

Atoms/molecules collide.

Atom/molecule gets energy.

Atom/molecule radiates.

Photon escapes from region.

Only the phases that cool relatively slowly will be seen in abundance.

Phases and Cooling, Part 2

If region is very high temperature ($> 10^6$ K), most atoms are ionized, so little opportunity to radiate. Hot ISM.

If region is $\sim 10^4$ K, hydrogen transitions aren't excited, and no molecules, so little radiation. Warm ISM.

If region is $\sim 10 - 100$ K, hydrogen molecules can't radiate, so little radiation. Molecular ISM.

Other temperatures cool very rapidly.

Summary

Interstellar medium has gas (and dust).

Densest are molecular clouds (nebulae).

Observe with molecular lines.

Also warm and hot phases.

All three phases have roughly same pressure.

Challenge: how does the ISM differ between types of galaxies?